Leveraging Terrestrial Industry for Utilization of Space Resources

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Presentation Topics

- **What is *In Situ* Resource Utilization (ISRU) and what are the space resources of interest?**
- **What are the approach, life cycle, and economic considerations for implementing ISRU?**
- **What are the site and infrastructure needs and implementation phasing for ISRU?**
- **What are the terrestrial industries and operations that are synergistic with ISRU?**
- **What are the challenges and similarities between ISRU and Terrestrial Industry that can be exploited?**
- **Where do we go from here?**

What is *In Situ* Resource Utilization (ISRU)?

ISRU involves any hardware or operation that harnesses and utilizes ‘in-situ’ resources to create products and services for robotic and human exploration

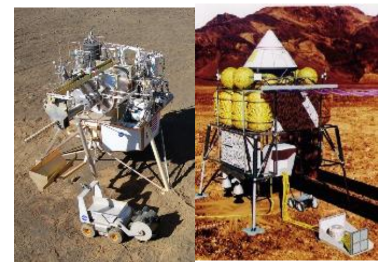
Resource Assessment (Prospecting)

Assessment and mapping of physical, mineral, chemical, and water resources, terrain, geology, and environment

Resource Acquisition

Atmosphere collection, drilling, excavation, transfer and preparation/ beneficiation before processing

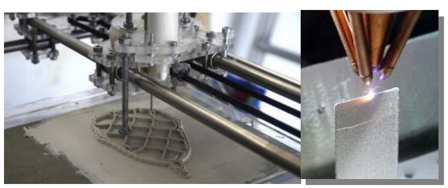
Resource Processing/ Consumable Production



Extraction and processing of resources into products with immediate use or as feedstock for construction & manufacturing

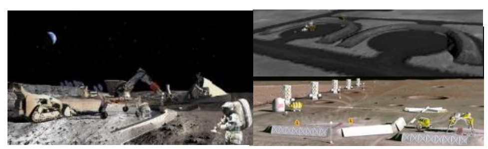
- Propellants, life support gases, fuel cell reactants, etc.

In Situ Manufacturing



Production of replacement parts, complex products, machines, and integrated systems from feedstock derived from one or more processed resources

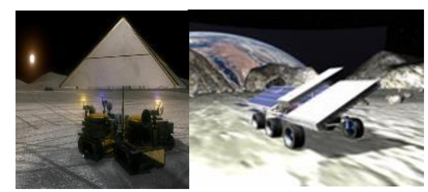
In Situ Construction



Civil engineering, infrastructure emplacement and structure construction using materials produced from *in situ* resources

- Radiation shields, landing pads, roads, berms, habitats, etc.

In Situ Energy



Generation and storage of electrical, thermal, and chemical energy with *in situ* derived materials

- Solar arrays, thermal storage and energy, chemical batteries, etc.

- **‘ISRU’ is a capability involving multiple elements to achieve final products** (mobility, product storage and delivery, power, crew and/or robotic maintenance, etc.)
- **‘ISRU’ does not exist on its own.** By definition it must connect and tie to users/customers of ISRU products and services

What are Space Resources?

- **'Resources'**
  - Traditional**:** **Water**, atmospheric gases, volatiles, solar wind volatiles, metals, alloys, etc.
  - Non-traditional: Trash and wastes from crew, spent landers and residuals, etc.
- **Energy**
  - Thermal Energy Storage Using Modified Regolith
    - Thermal conductivity of unmodified lunar regolith is very low (~1 mW/m-K); good insulator.
  - Permanent/Near-Permanent Sunlight
    - Stable thermal control & power/energy generation and storage
  - Permanent/Near-Permanent Darkness
    - Thermal cold sink for cryo fluid storage & scientific instruments
- **Environment**
  - Vacuum
  - Micro/Reduced Gravity
  - High Thermal Gradients
  - Atmosphere Drag
- **Location**
  - Stable Locations/'Real Estate':
    - Earth viewing, sun viewing, space viewing, staging locations
  - Isolation from Earth
    - Electromagnetic noise, hazardous testing & development activities (nuclear, biological, etc.), extraterrestrial sample curation & analysis, storage of vital information, etc.

Mission Variables for Implementation of ISRU

Location	Moon, Mars, Mars Moons, Near-Earth Asteroids
Resource Location Factors	Slopes, craters, rock size/distribution, geographic location (poles, equator)
Environmental Factors	Climate (temp., wind, season), pressure/vacuum, sunlight, gravity
Resource Demanded	Atmosphere/Gases (carbon dioxide), Water/Ice, Volatiles (hydrogen, helium), Metals (iron, nickel, titanium), Non-Metals (silicon)
Resource Extraction Method	Gas separation and compression, surface regolith mining, quarry mining, subsurface mining/extraction
Resource Pre-Processing and Transportation	Sorting, crushing/sizing, beneficiation; rovers, augers, conveyors, pneumatic
Resource Processing	Electrical, chemical, thermal
Resource Usage	Human consumables, propellants, stored energy, construction, manufacturing

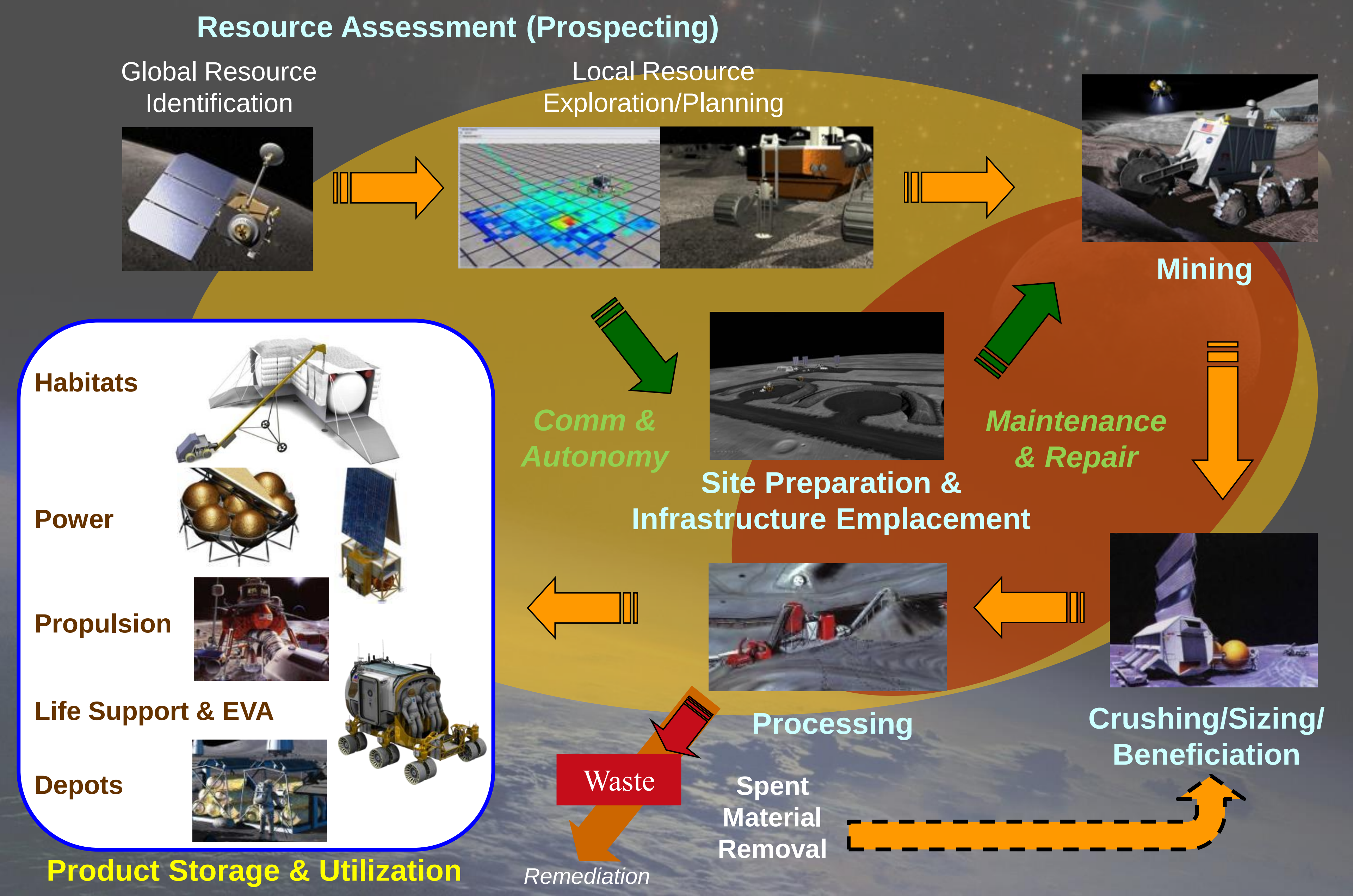
Main *Natural* Space Resources of Interest

	Moon	Mars	Asteroids	Uses
Water	Icy Regolith in Permanently Shadowed Regions (PSR) Solar wind hydrogen with Oxygen	Hydrated Soils/Minerals: Gypsum, Jarosite, Phylosilicates, Polyhdrated Sulfates Subsurface Icy Soils in Mid-latitudes to Poles	Subsurface Regolith on C-type Carbonaceous Chondrites	▪ Drinking, radiation shielding, plant growth, cleaning & washing ▪ Making Oxygen and Hydrogen
Oxygen	Minerals in Lunar Regolith: Ilmenite, Pyroxene, Olivine, Anorthite	Carbon Dioxide in the atmosphere (~96%)	Minerals in Regolith on S-type Ordinary and Enstatite Chondrites	▪ Breathing ▪ Oxidizer for Propulsion and Power
Carbon	▪ CO, CO_2, and HC's in PSR ▪ Solar Wind from Sun (~50 ppm)	Carbon Dioxide in the atmosphere (~96%)	Hydrocarbons and Tars (PAHs) in Regolith on C-type Carbonaceous Chondrites	▪ Fuel Production for Propulsion and Power ▪ Plastic and Petrochemical Production
Metals	Minerals in Lunar Regolith ▪ Iron/Ti: Ilmenite ▪ Silicon: Pyroxene, Olivine, Anorthite ▪ Magnesium: Mg-rich Silicates ▪ Al:: Anorthitic Plagioclase	Minerals in Mars Soils/Rocks ▪ Iron: Ilmenite, Hematite, Magnetite, Jarosite, Smectite ▪ Silicon: Silica, Phyllosilicates ▪ Aluminum: Laterites, Aluminosilicates, Plagioclase ▪ Magnesium: Mg-sulfates, Carbonates, & Smectites, Mg-rich Olivine	Minerals in Regolith/Rocks on S-type Stony Iron and M-type Metal Asteroids	▪ *In situ* fabrication of parts ▪ Electical power transmission

OXIDIZER
5.1

Similar Resources and Needs Exist at Multiple Locations

Space 'Mining' Cycle: *Prospect to Product*



ISRU Implementation Life Cycle

Identify Resource & Products

Resource Definition
- Determine Resource Utilization End Goals
- Initial Feasibility Study
- Multi-Site Evaluation
- Initial Cost Analysis
- Weigh Alternatives
- **Go/No-Go Decision**
- Plan Program and Approach

Prospecting
- Site Selection
- Site Imaging/ Characteriza-tion
- Resource Identification and Verification

Resource Analysis
- Estimate Reserve Size
- Test/Sample Resource Quality
- Understand Geotechnical Properties of Minerals
- Resource Analysis for Other Potential Uses/Users
- Assess Return On Investment

Mining Technology Readiness
- Demonstrate ‘Scalable’ Hardware & Operations for All Processes from Extraction to Product Storage
- Evaluate Processing Options

Establish Site & Operations

Site-Mine Planning
- Select Mining Site
- Environmental Analysis
- Electronic Modeling & Simulation
- Develop Power Sources
- Infrastructure Analysis
- Design Transportation and Comm.
- Contingency Planning

Site-Mine Development
- Infrastructure Development/ Set up
- Site Preparation, Landing, and Roads
- Construct Infrastructure and Processing Facilities

Perform Mining Ops

Site-Mine Operations & Maintenance
- Excavation
- Resource Extraction
- Manage Operations
- Remediate Site as Needed

Processing
- Sort and Refine Resources
- Process Resources Into Feedstocks
- Resource Transfer
- Recycle or Repurpose Wastes or Byproducts for Useful Purposes

Product and Application
- Export Resources from Site
- Convert Resource to Finished Product
- Deliver to End Users

Pilot – Non Human Mission Critical

Decision: Is Exploitation of Resources Beneficial?

Decision: Are Resources, Site, & Technology Viable for Exploitation?

Milestone: Is Site & Infrastructure Ready for Initial Mining?

Decision: Is Initial Mining and Product Viable for Mission Critical Use?

Human Mission Critical

Decision: Are Resources, Site, & Technology Viable for Full Mining?

Milestone: Is Site & Infrastructure Ready for Full Mining?

Economics of ISRU for Space Applications (1)

A 'Useful' Resource Depends on the Location, What is needed, How much is needed, How often it is needed, and How difficult is it to extract the resource

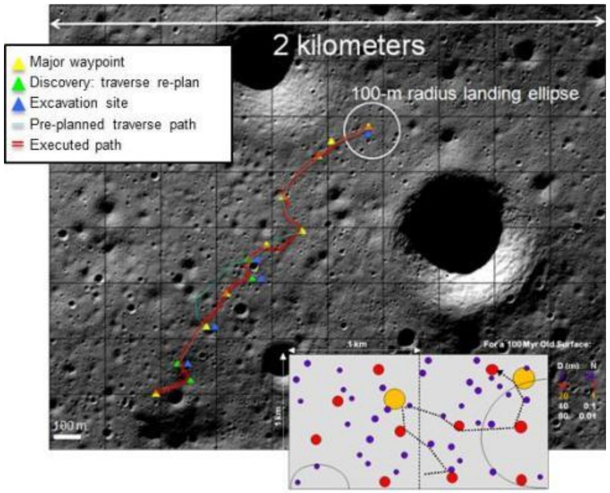
- **Location**
  - Resource must be assessable: slopes, rock distributions, surface characteristics, etc.
  - Resource must be within reasonable distance of mining infrastructure: power, logistics, maintenance, processing, storage, etc.
  - Resource must be within reasonable distance of transportation and delivery of product to 'market': habitats, landers, orbital depots, etc.

- **Resource extraction must be 'Economical'**
  - **Concentration and distribution of resource and infrastructure needed to extract and process the resource must allow for Return on Investment (ROI)** for:
    - Mass ROI - mass of equipment and unique infrastructure compared to brining product and support equipment from Earth. Impacts number and size of launch vehicles from Earth
    - Cost ROI - cost of development and certification of equipment and unique infrastructure compared to elimination of launch costs or reuse of assets (ex. reusable vs single use landers)
    - Time ROI - time required to notice impact of using resource: extra exploration or science hardware, extended operations, newly enabled capabilities, etc.
    - Mission/Crew Safety ROI - increased safety of product compared to limitations of delivering product from Earth: launch mass limits, time gap between need and delivery, etc.
  - **Amount of product needed must justify investment in extraction and processing**
    - Requires long-term view of exploration and commercialization strategy to maximize benefits
    - Metric: mass/year product vs mass of Infrastructure
  - **Transportation of product to 'Market' (location of use) must be considered**
    - Use of product at extraction location most economical

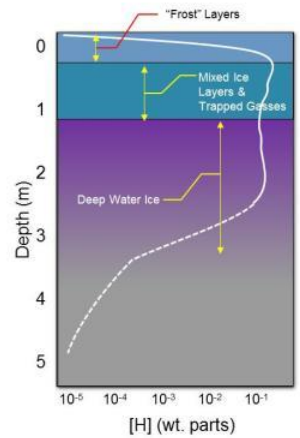
Economics of ISRU for Space Applications (2)

Need to assess the extent of the resource ‘ore body’

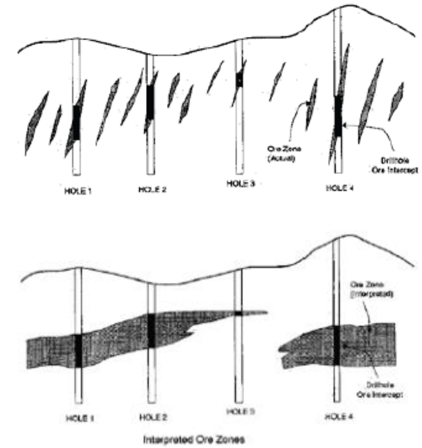
Need to Evaluate Local Region (1 to 5 km)



Need to Determine Vertical Profile



Need to Determine Distribution



Need to assess What is needed, How much is needed, How often it is needed

- **Resource Product Needs**

Location	Product	Amount (kg)	Need/Time	Use
Moon	O_2	1000	Per Year	Crew Breathing - Life Support Consumable Makeup
	O_2	3000 - 3500	2x Per Year	Non-Reusable Crew Ascent Vehicle Propulsion - Surface to Low Lunar Orbit: Earth fuel
	O_2	~16000	2x Per Year	Reusable Ascent/Descent Propulsion - Surface to L_1/L_2: Earth Fuel (4000 kg payload)
	O_2/H_2	~30,000	2x Per Year	Reusable Ascent/Descent Propulsion - Surface to L_1/L_2 (4000 kg payload)
	H_2O	150,000	2x Per Year	Lunar Human Outpost & Reusable Transportation
	O_2/H_2	150,000	Per Year	Anount needed for Propellant Delivery to LDRO for Human Mars Mission
Mars	O_2/CH_4	22,728/6978	Per Use/1x 480 Days	Non-Reusable Crew Ascent Vehicle Propulsion - Surface to High Mars Orbit
	O_2/CH_4	59,000/17,100	Per Use/1 or2x Per Yr	Reusable Ascent/Descent Propulsion - Surface to Mars Orbit
	H_2O	3,075	Surface/500 Days	Life Support System Closure
	H_2O	15,700	Per Use/1x 480 Days	Extracted H_2O to Make Non-Reusable Ascent Vehicle Propellant
	H_2O	38,300	Per Use/1 or2x Per Yr	Extracted H_2O to Make Reusable Ascent/Descent Vehicle Propellant

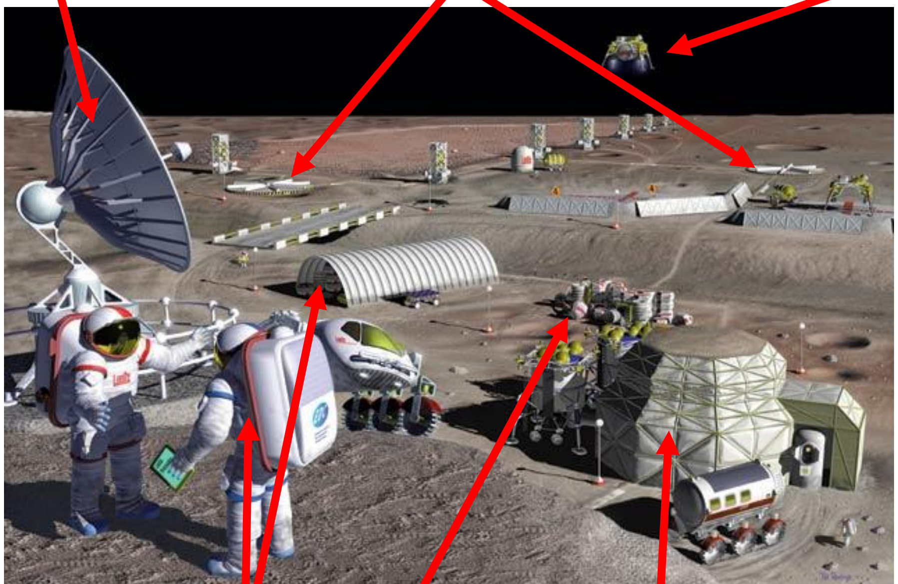
ISRU is Similar to Establishing Remote Mining Infrastructure and Operations on Earth

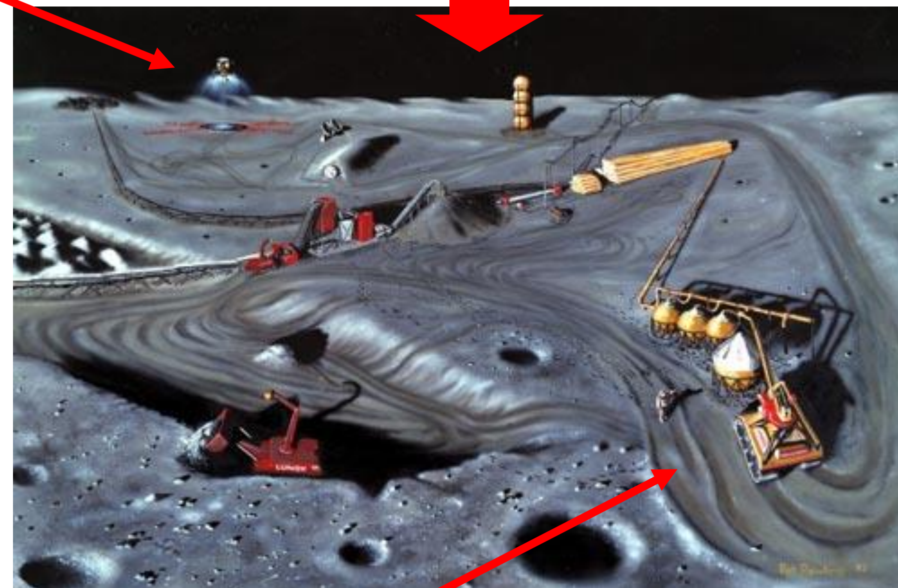
Transportation to/from Site:
- Navigation
- Loading & Off-loading
- Fuel & Support Services

Planned, Mapped, and Coordinated Mining Ops:
Areas for: i) Excavation, ii) Processing, and iii) Tailings

Communications

Power

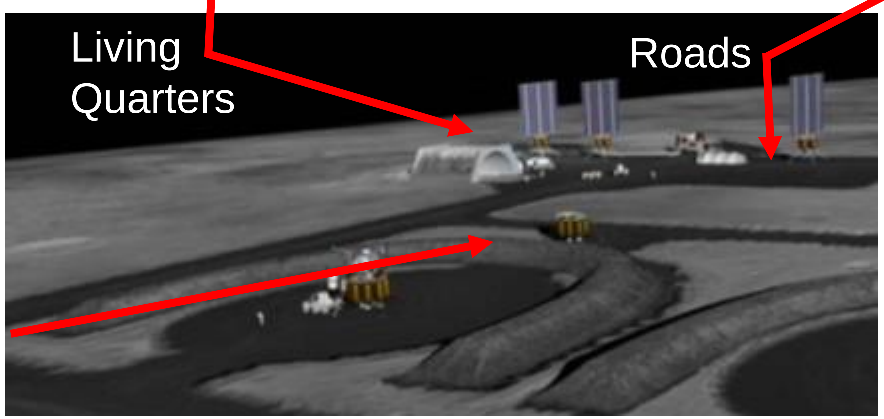




Maintenance & Repair

Logistics Management

Construction and Emplacement

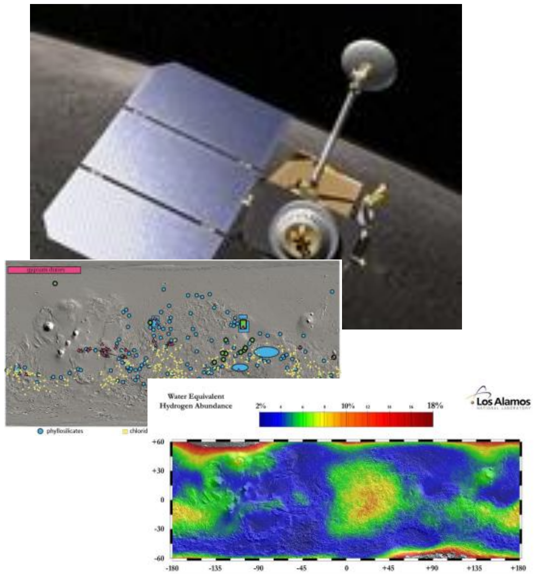


Approach to Resource Assessment

Knowledge Need, Risk Acceptability, Funding Availability, Time

Remote Assessment

Orbiters



Goals:

i. Obtain data on terrain, minerals, and water resources to select landing sites of consideration

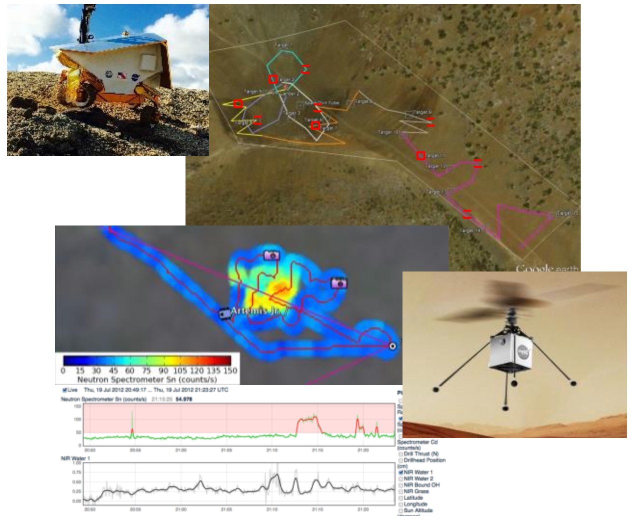
ii. Obtain data at resolution to plan surface Exploratory Assessment of terrain and resources

Instruments

- Better mineral resolution for chemistry and hydration
- Passive and active subsurface hydrogen and layer

Exploratory Assessment

Rovers, Hoppers, Aerial Vehicles, Impactors, Instrumented Landers



Goals:

i. Obtain data on physical/mineral characteristics and water/volatiles.

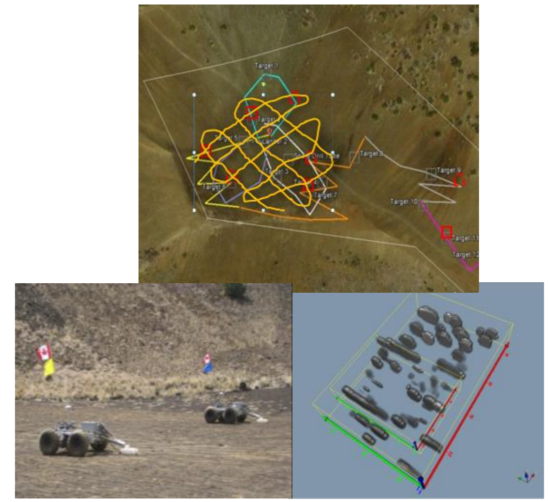
ii. Obtain sufficient data to determine if the site warrants a Focused Assessment of resources

Instruments

- Should cover physical/geotech, chemical/mineral, and volatile characterization
- Passive and active subsurface assess

Focused Assessment, Mapping, & Planning

Rover or Crew



Goals:

i. Ensure sufficient resources exist in form and location expected

ii. Build 3-D interpretation of data to define resource for mining operations

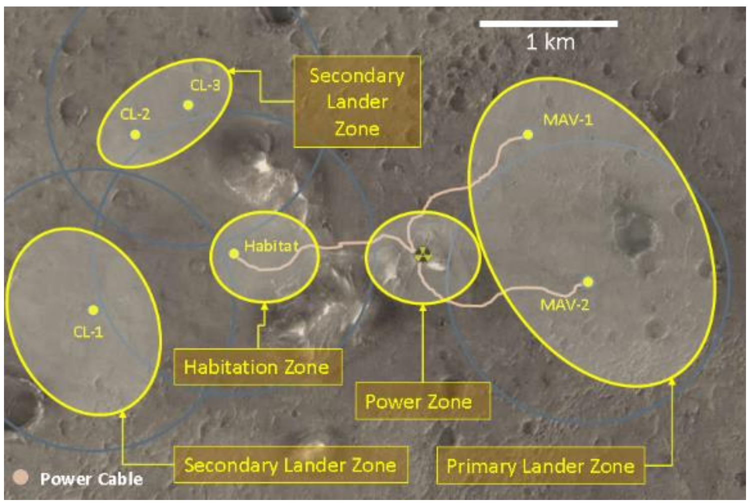
Instruments

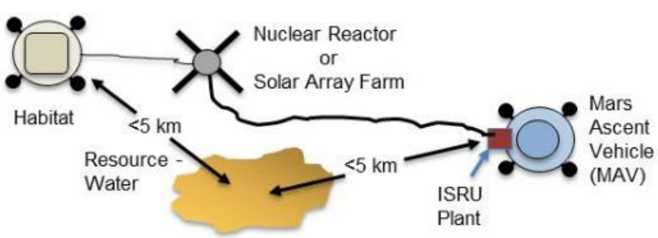
- Should cover physical, chemical/mineral, and volatile characterization
- Passive and active subsurface assess

ISRU Products, Operations, and Resources Grow As Mission Needs and Infrastructure Grow

Initial Conditions:

- Hardware delivered by multiple landers before crew arrives; Multiple landing zones
- Elements offloaded, moved, deployed, and connected together remotely
- 12-18 month stay for crew of 4 to 6; Gaps of time between missions where crew is not present
- Each mission delivers extra hardware & logistics

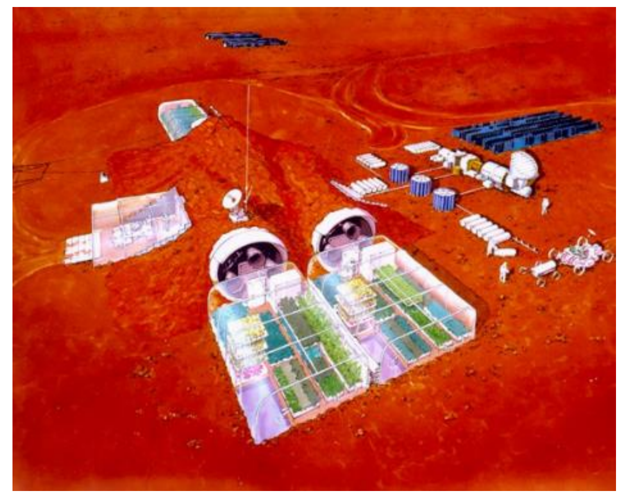


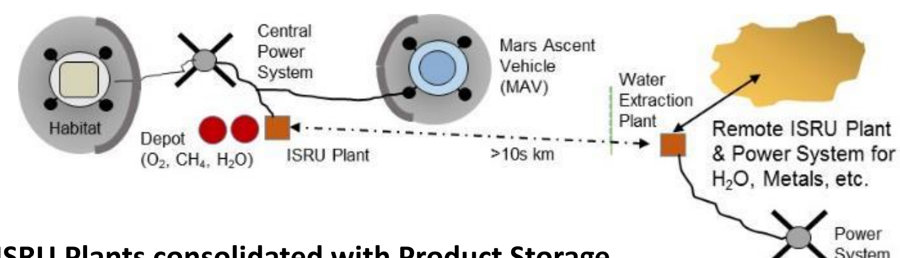


- **ISRU hardware integrated with Landers**
- **Resource very close to landing site/Ascent vehicle**

Ultimate Goal

- Consolidated and integrated infrastructure
- Indefinite stay with larger crews
- Roam (and mine) anywhere within 200 km diameter Exploration Zone
- Earth independent; *In situ* ability to grow infrastructure: power, habitation, food, parts, etc.





- **ISRU Plants consolidated with Product Storage**
- **Civil Engineering and In Situ Construction operations**
- **Resources can be farther from Habitat and Ascent Vehicle**

ISRU Product/Resource Processing Options Under Consideration

Oxygen/Fuel Production from Mars Atmosphere

Water/Volatile Extraction From Soils

Oxygen Extraction from Minerals

Metal Extraction from Minerals

Atmosphere Collection
- Dust Filtration
- Gas Separation (CO_2,N_2, Ar)
- Gas Pressurization (0.1 to >15 psia)
  - Pumps/Compressors
  - Cryogenic Separation
  - Adsorption

Chemical Processing
- CO_2 Reduction
  - Solid Oxide Electrolysis
  - Reverse Water Gas Shift
  - Bosch
- Fuel Production
  - Sabatier (CH_4)
  - Fischer Tropsch
  - Alcohols
  - Ethylene → Plastics
- Water Processing
  - Water Electrolysis (PEM vs SOE)
  - Water Cleanup/Deionization

Solid Extraction and Transport
- Granular Soil Excavation/Extraction
  - Drills/Augers (1 to 3 m)
  - Load/Haul/Dump (LHD)
  - Bucket Wheels/Drums
- Consolidated Material Extraction & Preparation
  - Drills/Augers
  - Percussive Blades
  - Ripper & LHD
  - Crushing & Sorting
- Regolith/Soil Transfer
  - Augers
  - Pneumatic
  - Bucket ladders

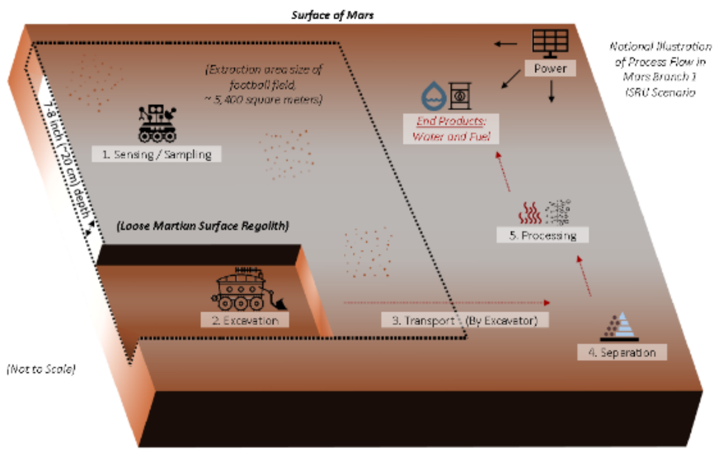
Water/Volatile Extraction
- Hydrated soils
  - Open Reactor/Heating
  - Closed Fluidized Reactor
  - Auger Dryer
- Icy soils
  - Transport to Reactor
  - Downhole Enclosure
  - Downhole Heating & Removal

Oxygen Extraction from Minerals
- Hydrogen Reduction of Iron Oxides
- Methane Reduction of Silicates
- Molten Oxide Reduction

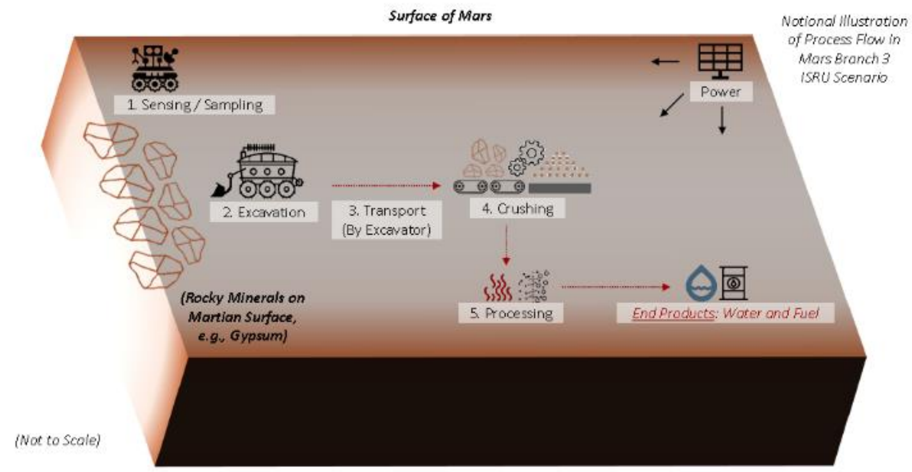
Metal Extraction from Minerals
- Molten Oxide Reduction
- Molten Salt Reduction
- Ionic Liquids/Acids
- Biological Extraction

Extra-Terrestrial Mining Operations Under Consideration

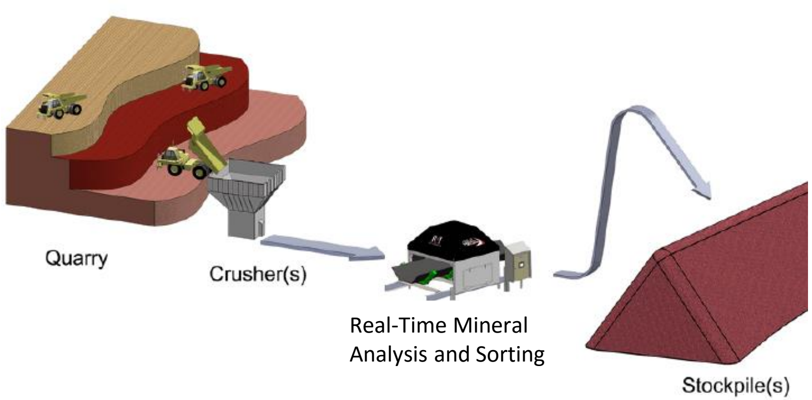
Granular Soil Resource



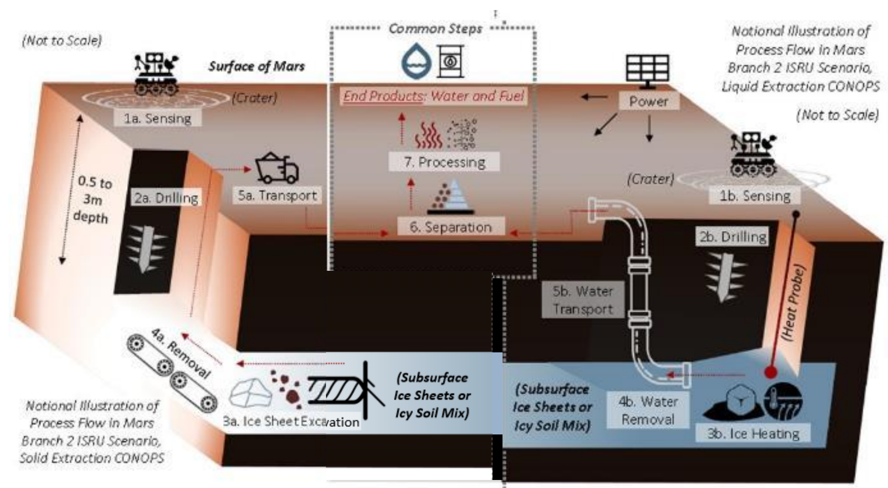
Hard Mineral Resource



Quarry Mining



Icy Resource/Subsurface Mining



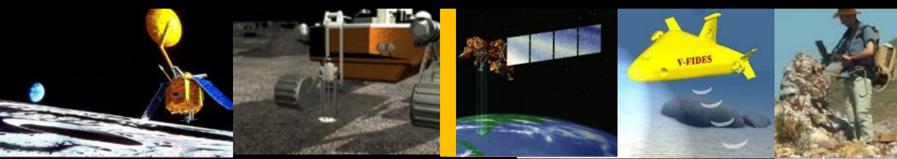
Asteroid mining (not shown here) under micro-gravity conditions may require unique mining technologies and operations compared to terrestrial and Moon/Mars surface operations

Key Considerations in Pursuing Terrestrial or Space Mining

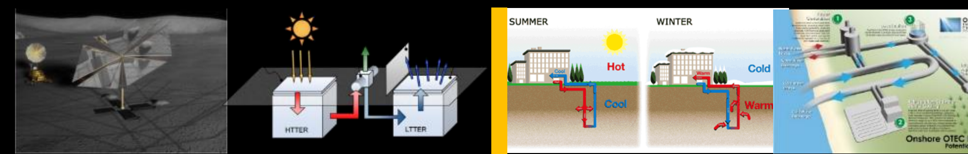
		Current Similarities/Differences
Equipment Requirements	Mass, complexity, and scale required for resource extraction, transfer, and processing	▪ Mass is not as big of an issue for terrestrial mining. ▪ Scale of space mining currently significantly smaller ▪ Minimizing complexity is important for both
Infrastructure Requirements	Support capabilities necessary for comm., nav., power, maintenance, personnel, and operations	▪ Minimizing infrastructure needs and time to establish infrastructure capabilities are critical for both ▪ Similar power, communication, and personnel needs
Energy Required	Type and amount of energy necessary for extraction & processing	▪ Energy efficiency more important for space mining ▪ Solar/renewable energy/power systems are more important for space mining
Transportation	Type, capability, frequency, and cost of transportation required to support operations and to ship products	▪ Minimizing transportation is important to both ▪ Shipment of cryogenic products more difficult than water or minerals
Location & Environment Adaptability	Adaptability of existing equipment and infrastructure to extreme temperatures and remote locations	▪ Adapting and operating in extreme temperature and abrasive environments is important to both ▪ Space mining has more extreme environments
Level of Autonomy Needed	Ability of equipment to function/operate with minimal or no oversight	▪ Tele-operation capabilities important to both ▪ Autonomy more important for space mining due to limited crew availability & communication time delays
Maintenance & Logistics Requirements	Level of equipment degradation/failure expected; Spares and personnel availability	▪ Minimizing logistics/spares is important to both for remote locations ▪ Minimizing maintenance more important for space mining due to limited crew availability
Environmental Impact & Regulations	Immediate and long-term impact on local environment; Regulations and restrictions on processing & operations	▪ Environmental impact, regulations, and restrictions are more important to terrestrial mining

There are A lot of Similarities between ISRU and Terrestrial Applications

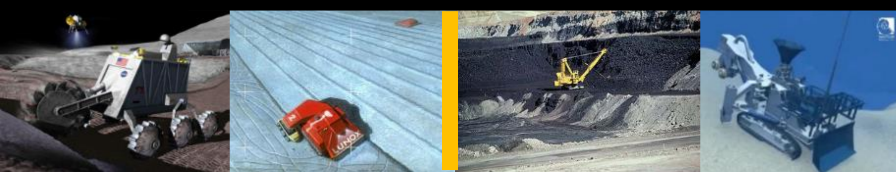
Prospecting for Resources



Thermal Energy



Mining for Resources



Alternative Energy (Fuel Cells & Trash to HC)

Resource Processing (Gases, Liquids, Solids)

Product Liquefaction, Storage, and Transfer

Civil Engineering & Construction

Remote Operations & Maintenance

Similar Needs for Terrestrial & Space Mining

Resource Prospecting

- Physical & Mineral Characterization Instrument Types
  - LIBS
  - GPR
  - Raman/IR
  - XRD/XRF
  - Hyperspectral
  - Shear Vane/Cone Penetrometer
- Miniaturization and Ruggedness of Instruments
- Data Integration, Display, and Analysis of Resources

Mining

- Mine Operation Planning Tools
- Mining Technologies
  - Excavation
  - Drilling
  - Consolidated Material Cutting/ Fracturing
  - Crushing/Sorting
  - Mineral Beneficiation
  - Transport
- Environmental Compatibility
  - Design for Thermal Extremes
  - Material Selection
  - Lubricants
  - Wear Resistant Coatings
- Equipment Testing Under Realistic Conditions
  - Soil Bins/Controlled Testing
  - Analog Test Sites/In-Mine Testing
  - Environmental Simulation Facilities
  - Actual or Simulated Materials (Simulants)

Processing

- Atmosphere Collection
  - Gas Compression
  - Atmosphere Filtration
- Chemical Processing
  - Hydrogen Production
  - Syngas Production and Conversion
  - CO/CO_2 Conversion to Fuel and Plastics
- Solids Processing
  - Granular Material Drying
  - Wear-Resistant Valves
- Metal Extraction (Oxygen Release)
  - Mineral Electrolysis
  - Acid Extraction
  - Biological Extraction

Remote Operations

- Mining Tele-operations
  - Approaches and Human Interfaces
  - Same as Mining Autonomy
- Mining Autonomy
  - Approaches
  - Avionics, Software, Instruments, Sensors, & Cameras Needed
  - Communications Infrastructure: Wireless, Bandwidth, Delays

Product Storage and Transfer

- Liquefaction for Oxygen and Hydrogen

Space Mining Needs

- Modular, Multi-Mission Infrastructure
  - Plug-and-Play
  - Lightweight
- High Density/Regenerable Energy - All Electric
  - Fuel Cells/Batteries vs Combustion Engines
  - Electro-Mechanical Actuators vs Hydraulics

ISRU Development and Implementation Challenges

Space Resource Challenges

- What resources exist at the site of exploration that can be used?
  - Are there enough of the right resources; Return on Investment
- What are the uncertainties associated with these resources?
  - Form, amount, distribution, impurities/contaminants
- How to address planetary protection requirements?

ISRU Technical Challenges

- Is it technically feasible to collect, extract, and process the resource?
- How to maximize performance/minimize mass
- How to achieve high reliability and minimal maintenance requirements?
- How to minimize power through thermal management integration and taking advantage of environmental conditions?

ISRU Operation Challenges

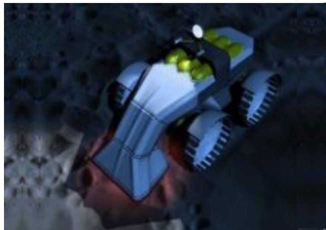
- How to operate in extreme environments, including temperature, pressure, dust, and radiation?
- How to achieve long duration, autonomous operation and failure recovery?
- How to operate in low gravity or micro-gravity environments?
  - Anchoring/weight-on-bit
  - Friction, cohesion, and electrostatic forces may dominate in micro-g

ISRU Integration Challenges

- How to optimize at the architectural level rather than the system level?
- How are other systems designed to incorporate ISRU products?
- How to manage the physical interfaces and interactions between ISRU and other systems?
- How to establish and grow production and infrastructure over time to achieve immediate and long-term Returns on Investment

Overcoming these challenges requires a multi-discipline and integrated approach

ISRU Has Common Challenges with Terrestrial Industry









Severe Environments
- Extreme temperatures
- Large changes in temperature
- Dust and abrasion
- No pressure vs Extreme pressure
- Environmental testing

Maintenance
- Minimal maintenance desired for long operations
- Performing maintenance is difficult in environments
- Minimize logistics inventory and supply train

Operations/Communication
- Autonomous and tele-operation;
- Delayed and potentially non-continuous communication coverage
- Local navigation and position information

Integration and Infrastructure
- Hardware from multiple countries must be compatible
- Common standards; Common interface
- Optimize at the architecture/operation level vs the individual element
- Establish and grow production and infrastructure over time to achieve immediate and long-term Returns on Investment

Return on Investment
- Need to have a return on investment to justify expense and infrastructure buildup
- Multi-use: space and terrestrial applications

ISRU: Where We Are Today

- **Most Prospecting, Excavation, and Consumable Production technologies, systems, and technologies have been shown to be feasible at subscale and for limited test durations**

- **Drivers**
  - **Hardware simplicity and robustness are as important as minimizing mass and power**
  - **Hardware commonality with other systems (propulsion, power, life support, thermal) can significantly reduce costs and logistics**

- **Work still required to:**
  - **Perform prospecting missions to better define resources**
  - **Scale up production and processing rates to human mission needs (*pilot scale for terrestrial industry*)**
  - **Operate hardware and systems under relevant mission environments; Understand how to take advantage of the environment and day/night cycle**
  - **Perform long-duration testing to understand hardware life, maintenance, and logistics needs**
  - **Add autonomy to operations, especially for mining operations**

- **Partnering with Terrestrial Industry and co-leveraging hardware is important to NASA**

Partnering: Terrestrial and Space Mining

- **Maintain and expand dialog with Industry**
  - **Examine similarities in Key Considerations and Needs**
  - **Address common challenges**
  - **Examine differences in Key Considerations to understand potential paradigm changes/technology infusion**

- **Examine use of Test Facilities and Approaches; especially for Environmental Compatibility**

- **Target ‘Spin-in/Spin-off’ Technology Relationships**
  - **Procurements/Request for Proposals (RFPs)**
  - **Cooperative Agreements**
  - **Space Act Agreements**

BACKUP

Terrestrial Resources and Industries Applicable to Spin-In/Spin-off with ISRU

Minerals Mining

Chemical Processing

Industrial Gases

Water Purification

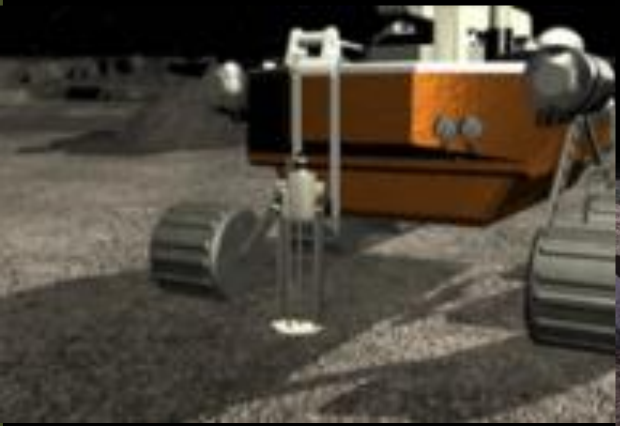
Renewable Energy

Thermal Energy

Waste Processing

Construction & Manufacturing

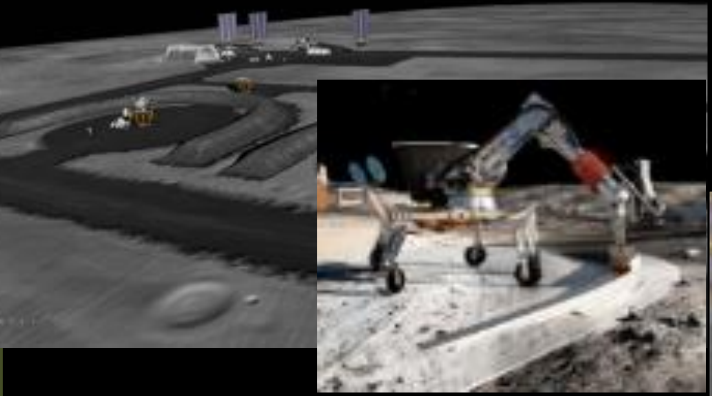
Lunar ISRU Mission Capability Concepts



Resource Prospecting – Looking for Polar Ice

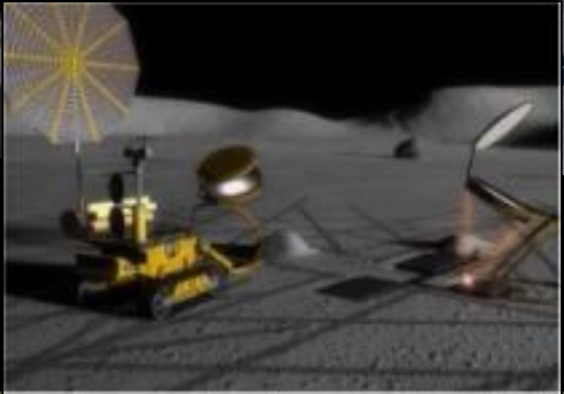
Excavation & Regolith Processing for O_2 Production

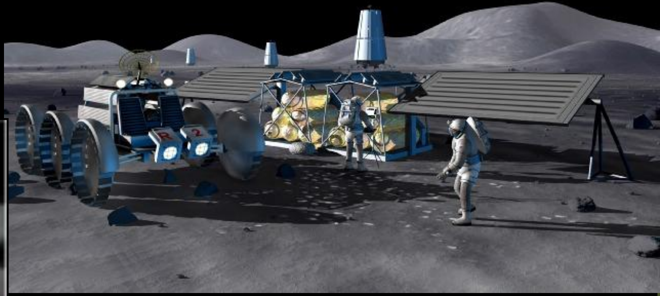
Carbothermal Processing with Altair Lander Assets



Landing Pads, Berms, Roads, and Structure Construction

Thermal Energy Storage Construction





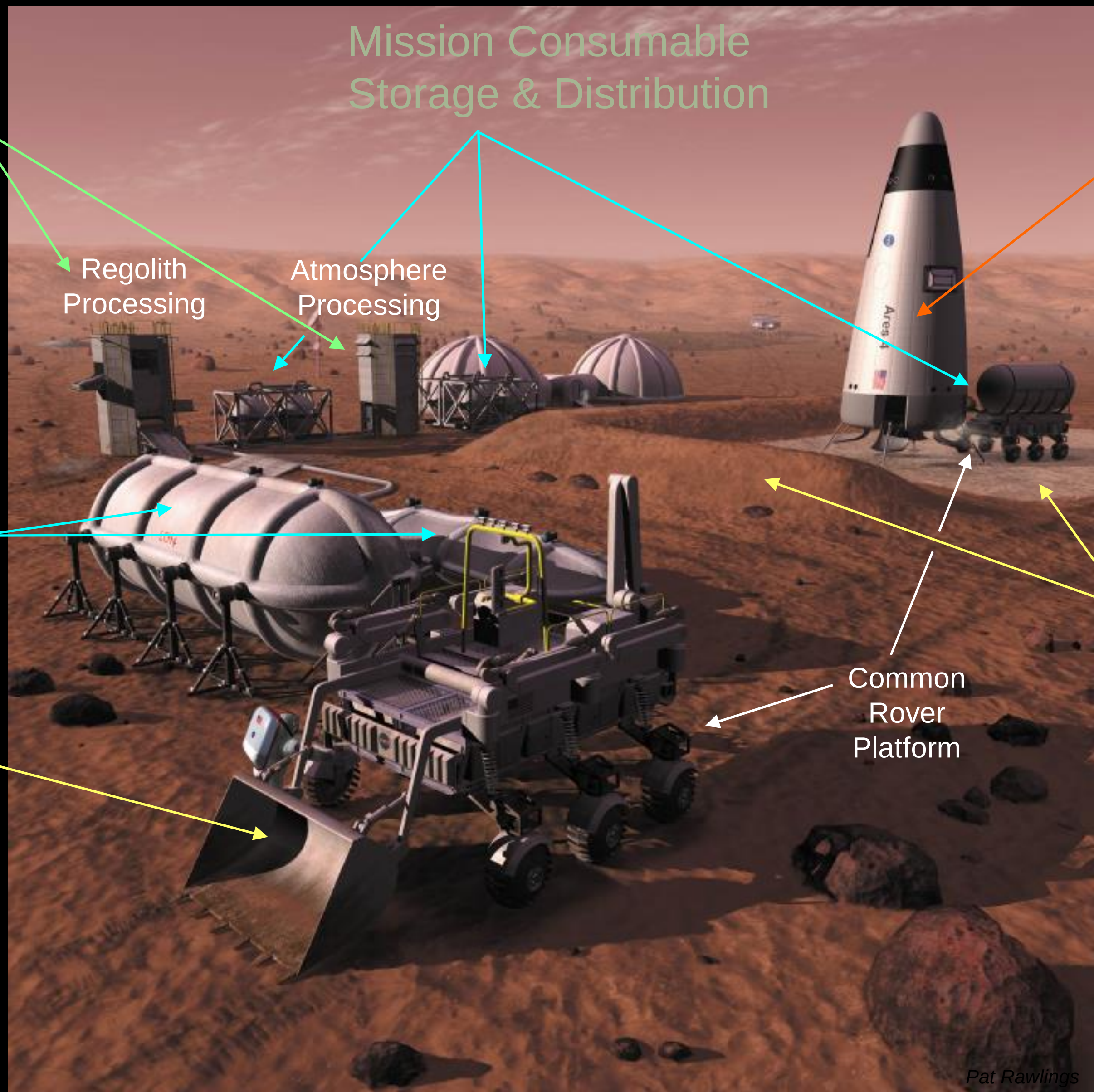
Consumable Depots for Crew & Power

Mars ISRU Mission Capability Concepts

Resource Processing Plants

Collapsible/ Inflatable Cryogenic Tanks

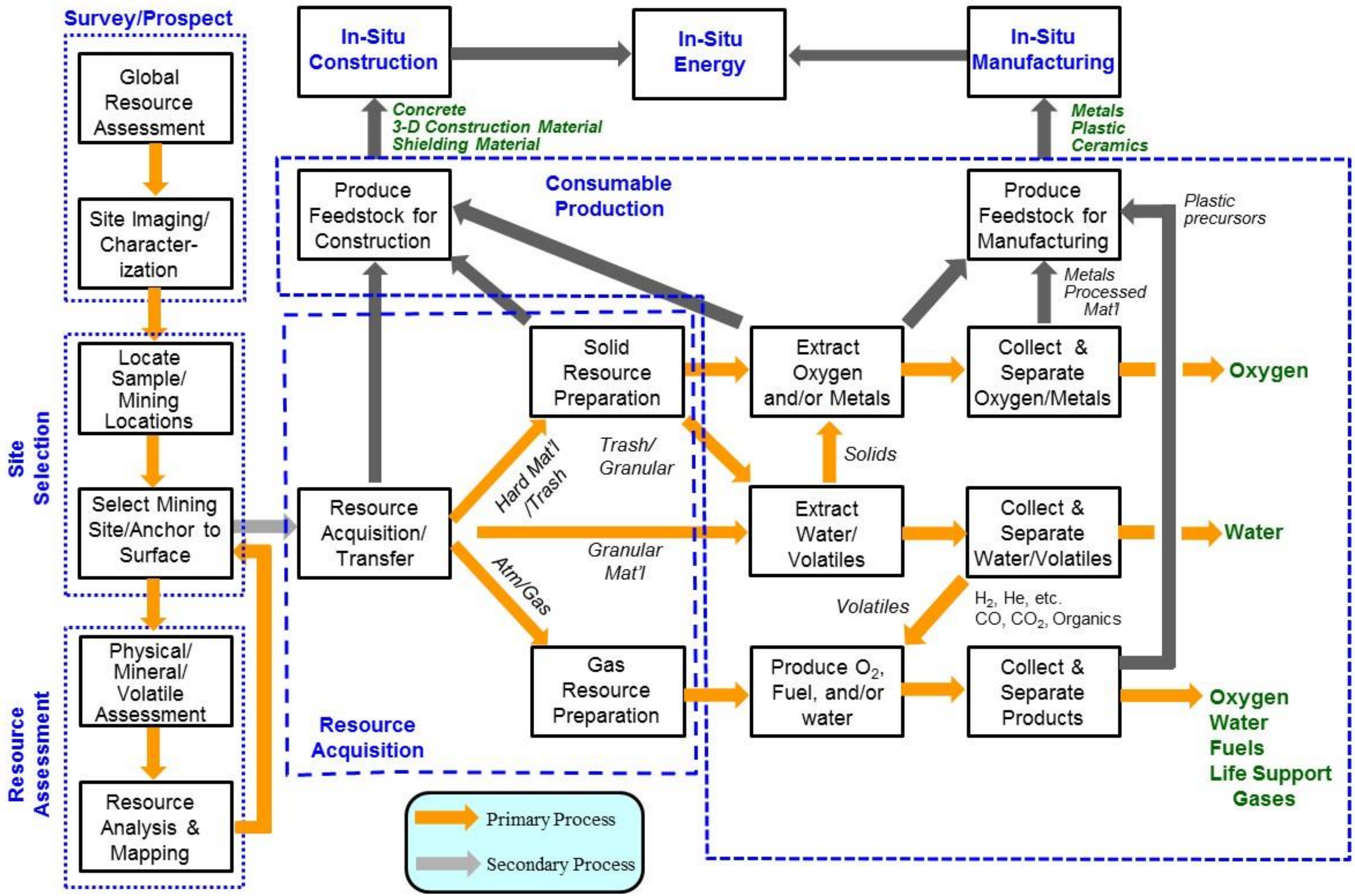
Multi-use Construction/ Excavator: resources, berms, nuclear power plant placement, etc.

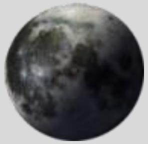


Reusable lander/ascent vehicle or surface hopper fueled with in-situ propellants

Landing pad & plume exhaust berm

ISRU Capability-Function Flow Chart





Natural Space Resources

Four major resources on the Moon:

- **Regolith**: oxides and metals
  - Ilmenite 15%
  - Pyroxene 50%
  - Olivine 15%
  - Anorthite 20%
- Solar wind volatiles in regolith
  - Hydrogen 50 – 150 ppm
  - Helium 3 – 50 ppm
  - Carbon 100 – 150 ppm
- **Water/ice** and other volatiles in polar shadowed craters
  - 1-10% (LCROSS)
  - Thick ice (SAR)
- Discarded materials: **Lander and crew trash and residuals**

Three major resources on Mars:

- **Atmosphere**:
  - 95.5% Carbon dioxide,
  - 2.7% Nitrogen,
  - 1.6% Argon
- **Water in soil**: concentration dependant on location
  - 2% to dirty ice at poles
- Oxides and metals in the soil

Resources of Main Interest

- **Oxygen**
- **Water**
- Hydrogen
- Carbon/CO_2
- Nitrogen
- Metals
- Silicon

~85% of Meteorites are Chondrites

Ordinary Chondrites 87%

FeO:Si = 0.1 to 0.5

Fe:Si = 0.5 to 0.8

Pyroxene
Olivine
Plagioclase
Diopside
Metallic Fe-Ni alloy
Trioilite - FeS

Source metals (Carbonyl)

Carbonaceous Chondrites 8%

Highly oxidized w/ little or no free metal

Abundant volatiles: up to 20% bound water and 6% organic material

Source of water/volatiles

Enstatite Chondrites 5%

Highly reduced; silicates contain almost no FeO

60 to 80% silicates; Enstatite & Na-rich plagioclase

20 to 25% Fe-Ni

Cr, Mn, and Ti are found as minor constituents

Easy source of oxygen (Carbothermal)

Lunar Resource Overview

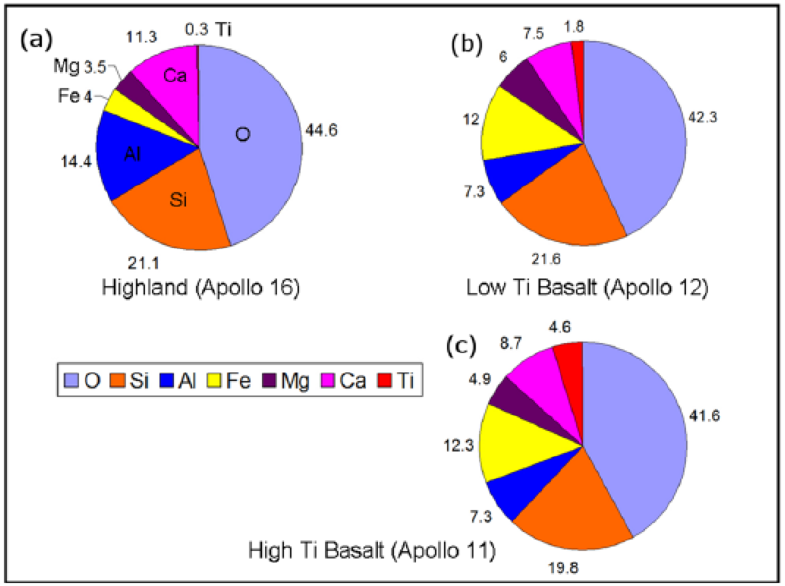


Figure 3. Example chemical compositions of lunar soils: (a) lunar highland minerals (Apollo 16); (b) low-Ti basalts (Apollo 12); and (c) high-Ti basalts (Apollo 11). Based on data collated by Stoeser et al. (2010), and reprinted from *Planetary and Space Science*, Vol. 74, Schwandt C, Hamilton JA, Fray DJ and Crawford IA, 'The production of oxygen and metal from lunar regolith' 49-56, Copyright (2012), with permission from Elsevier.

Table 1. Average concentrations of solar wind implanted volatiles in the lunar regolith (Fegley and Swindle 1993), where the quoted errors reflect the range (± one standard deviation) of values found at different sampling locations. The corresponding average masses contained within 1 m^3 of regolith (assuming a bulk density of 1660 kg m^{-3}; Carrier et al., 1991) are also given.

Volatile	Concentration ppm (μg/g)	Average mass per m^3 of regolith (g)
H	46 ± 16	76
^{3}He	0.0042 ± 0.0034	0.007
^{4}He	14.0 ± 11.3	23
C	124 ± 45	206
N	81 ± 37	135
F	70 ± 47	116
Cl	30 ± 20	50

In addition to the volatiles listed in Table 1, lunar soils contain small quantities (typically ≤ 1 μg/g) of the solar wind derived noble gasses Ne and Ar (and much smaller quantities of Kr and Xe). Perhaps more interesting from a resource perspective, they also contain a significant quantity of sulphur (715±216 μg/g; Fegley and Swindle 1993), mostly derived from the mineral troilite (FeS), and this would probably also be released by any process which extracts the other volatile elements.

From "Lunar Resources: A Review" by Ian Crawford,2015

		Lunar Basalt	Lunar Breccias	Lunar Soil	Earth Crust
Pr	ppm	13	---	7	9.2
Nd	ppm	63	40	39	41.5
Sm	ppm	21	14	13	7.05
Eu	ppm	2.2	1.9	1.7	2
Gd	ppm	27	20	15	6.2

Rare Earth Elements

		Lunar Basalt	Lunar Breccias	Lunar Soil	Earth Crust
Ag	ppb	1.5	18	9	75
Cd	ppb	10	100	50	150
In	ppb	3	5	<10	25
Te	ppb	16	72	---	1
Se	ppm	0.7	1.6	0.8	0.05

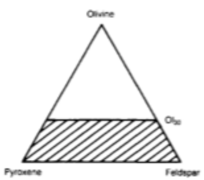
Vapor Mobilized Elements

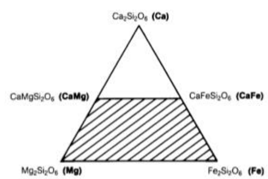
From Bob Wegeng/PNNL

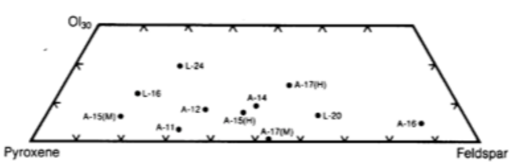
TABLE 5.1. Modal proportions (vol.%) of minerals and glasses in soils from the Apollo (A) and Luna (L) sampling sites (90–20 μm fraction, not including fused-soil and rock fragments).

	A-	A-	A-14	A- (H)	A- (M)	A-16	A- (H)	A- (M)	L-16	L-20	L-
Plagioclase	21.4	23.2	31.8	34.1	12.9	69.1	39.3	34.1	14.2	52.1	20.9
Pyroxene	44.9	38.2	31.9	38.0	61.1	8.5	27.7	30.1	57.3	27.0	51.6
Olivine	2.1	5.4	6.7	5.9	5.3	3.9	11.6	0.2	10.0	6.6	17.5
Silica	0.7	1.1	0.7	0.9	-	0.0	0.1	-	0.0	0.5	1.7
Ilmenite	6.5	2.7	1.3	0.4	0.8	0.4	3.7	12.8	1.8	0.0	1.0
Mare Glass	16.0	15.1	2.6	15.9	6.7	0.9	9.0	17.2	5.5	0.9	3.4
Highland Glass	8.3	14.2	25.0	4.8	10.9	17.1	8.5	4.7	11.2	12.8	3.8
Others	-	-	-	-	2.3	-	-	0.7	-	-	
Total	99.9	99.9	100.0	100.0	100.0	99.9	99.9	99.8	100.0	99.9	99.9

Data from *Papike et al.* (1982), *Simon et al.* (1982), *Laul et al.* (1978a), and Papike and Simon (unpublished). (H) Denotes highland. (M) Denotes mare.







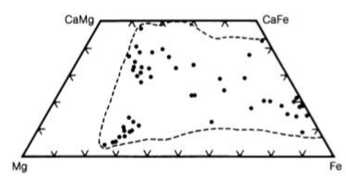


TABLE 5.2. Summary of modal data (vol.%) for mare basalts (after *BVSP*, 1981, p. 255).

	Oxide Minerals	Pyroxen e	Feldspa r	Olivine
A-17 high Ti	24.4	47.7	23.4	4.6
A-11 high K	20.6	57.5	21.7	0.1
A-17 low K	15.1	51.6	33.3	-
A-11 low K	14.6	50.9	32.2	2.3
A-12 ilmenite	9.3	61.1	25.9	3.6
A-12 pigeonite	9.1	68.4	21.1	1.4
A-12 olivine	7.1	53.5	19.2	20.2
L-16 aluminous	7.1	51.5	41.2	0.1
A-15 olivine	5.5	63.3	24.1	7.0
A-15 pigeonite	3.7	62.5	33.8	-
A-14 aluminous	3.2	53.8	43.0	-
L-24 ferrobasalt	1.8	48.6	39.1	10.4
L-24	1.4	60.2	34.2	4.2
ferrobasalt	1.0	61.7	31.9	5.4
A-17 VLT				

Modal data normalized to 100% for the four phases considered, in Apollo (A) and Luna (L) samples. Ordered from top to bottom in terms of decreasing modal content of opaque oxide minerals.

contains some Mg substituting for Fe (Table A5.11), which arises from the solid solution that exists between ilmenite ($FeTiO_3$) and $MgTiO_3$, the mineral *geikielite*. Other elements are present only in minor to trace amounts (i.e., <1%); these include Cr, Mn, Al, and V. In addition, ZrO_2 contents of up to 0.6% have

Lunar Polar Volatiles
(Observed at LCROSS Site)

					Instrument			
	Column Density (# m^{-2})	Relative to H2O(g) (NIR spec only)	Concentration (%)	Long-term Vacuum Stability Temp (K)	UV/Vis	NIR	LAMP	M3
CO	1.7e13±1.5e11		5.7	15			x	
H_2O(g)	5.1(1.4)E19	1	5.50	106		x		
H_2	5.8e13±1.0e11		1.39	10			x	
H_2S	8.5(0.9)E18	0.1675	0.92	47	x	x		
Ca	3.3e12±1.3e10		0.79				x	
Hg	5.0e11±2.9e8		0.48	135			x	
NH_3	3.1(1.5)E18	0.0603	0.33	63		x		
Mg	1.3e12±5.3e9		0.19				x	
SO_2	1.6(0.4)E18	0.0319	0.18	58		x		
C_2H_4	1.6(1.7)E18	0.0312	0.17	~50		x		
CO_2	1.1(1.0)E18	0.0217	0.12	50	x	x		
CH_3OH	7.8(42)E17	0.0155	0.09	86		x		
CH_4	3.3(3.0)E17	0.0065	0.04	19		x		
OH	1.7(0.4)E16	0.0003	0.002	>300 K if adsorbed	x	x		x
H_2O (adsorb)			0.001-0.002					x
Na		1-2 kg		197	x			
CS					x			
CN					x			
NHCN					x			
NH					x			
NH_2					x			

Volatiles comprise possibly 15% (or more) of LCROSS impact site regolith

*Chart courtesy of Tony Colaprete

Lunar Polar Volatile and Their Uses

Primary	Secondary	Uses
H_2O		▪ Drinking water, washing, EVA coolant, radiation shielding ▪ Steam reforming of hydrocarbons
	O_2	▪ Life support/breathing ▪ Rocket oxidizer, fuel cell reactant
H_2	$2H_2$	▪ Rocket fuel, fuel cell reactant ▪ Key reactant in petro-chemical industry
CO/CO_2		▪ Key reactant in hydrocarbon rocket fuel & petro-chemical industry
NH_3	$3H_2$	▪ Thermal control fluid, cleaning agent ▪ Fuel cell reactant
	N_2	▪ Life support buffer gas, inert gas for science, purge gas
H_2S		▪ *Contaminant; potential production of sulfuric acid*
	H_2	
	S	▪ *????*
CH_4/ C_2H_4/ CH_3OH		▪ Rocket fuel, fuel cell reactant ▪ Key reactant in hydrocarbon rocket fuel & petro-chemical industry

Mars Resources

Resource	Potential Mineral Source	Reference
Water, Hydration/ Hydroxyl	Gypsum – ($CaSO_4.2H_2O$) Jarosite – ($KFe^{3+}{}_3(OH)_6(SO4)_2$) Opal & hydrated silica – ($SiO_2.nH_2O$) Phyllosilicates Other hydrated minerals (TBR)	Horgan, et al.(2009), Distribution of hydrated minerals in the north polar region of Mars, J. Geophys. Res., 114, E01005 Mustard et al.(2008), Hydrated silicate minerals on Mars observed by the Mars Reconnaissance Orbiter CRISM instrument, Nature 454, 305-309
Water, Ice	Icy soils Glacial deposits	Mellon & Feldman (2006) Dickson et al. (2012)
Iron*	Hematite, Jarosite Magnetite, Triolite Laterites, Ilmenite	Ming et al. (2006), Geochemical and mineralogical indicators for Aqueous processes in Columbia Hills of Gusev Crater, Mars" JGR 111, E02S12 Poulet et al. (2007), Martian surface mineralogy from OMEGA/Mex: Global mineral maps" JGR 112, E08S02
Aluminum*	Laterites, Plagioclase Aluminosilicates, Scapolite	
Magnesium*	Mg-sulfates, Mg-rich olivines, Forsterite	
Silicon	Pure amorphous silica Hydrated silica Phyllosilicates	Rice et al. (2010), "Silica-rich deposits and hydrated minerals at Gusev Crater, Mars: Vis-NIR spectral characterization and regional mapping" Icarus 205 (2010) 375–395
Titanium*	Ilmenite, Titanomagnetite	Ming et al. (2006), JGR 111, E02512

	Oxides (Wt%)													Elements (ppm)			
	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cr_2O_3	Cl	SO_3	Ni	Zn	Br	Ge
MER Spirit – Laguna Soils, Panda Subclass	46.8	0.79	10.5	16.1	0.33	9.6	6.2	3	0.38	0.75	0.35	0.6	4.6	684	190	42	6
Rocknest Soil (Portage)	43.0	1.2	9.4	19.2	0.42	8.7	7.3	2.7	0.49	0.95	0.49	0.69	5.5	456	326	34	
Mojave Mars Simulant	49.4	1.09	17.1		0.17	6.1	10.5	3.3	0.48	0.17	0.05		0.1	118	71		0.07

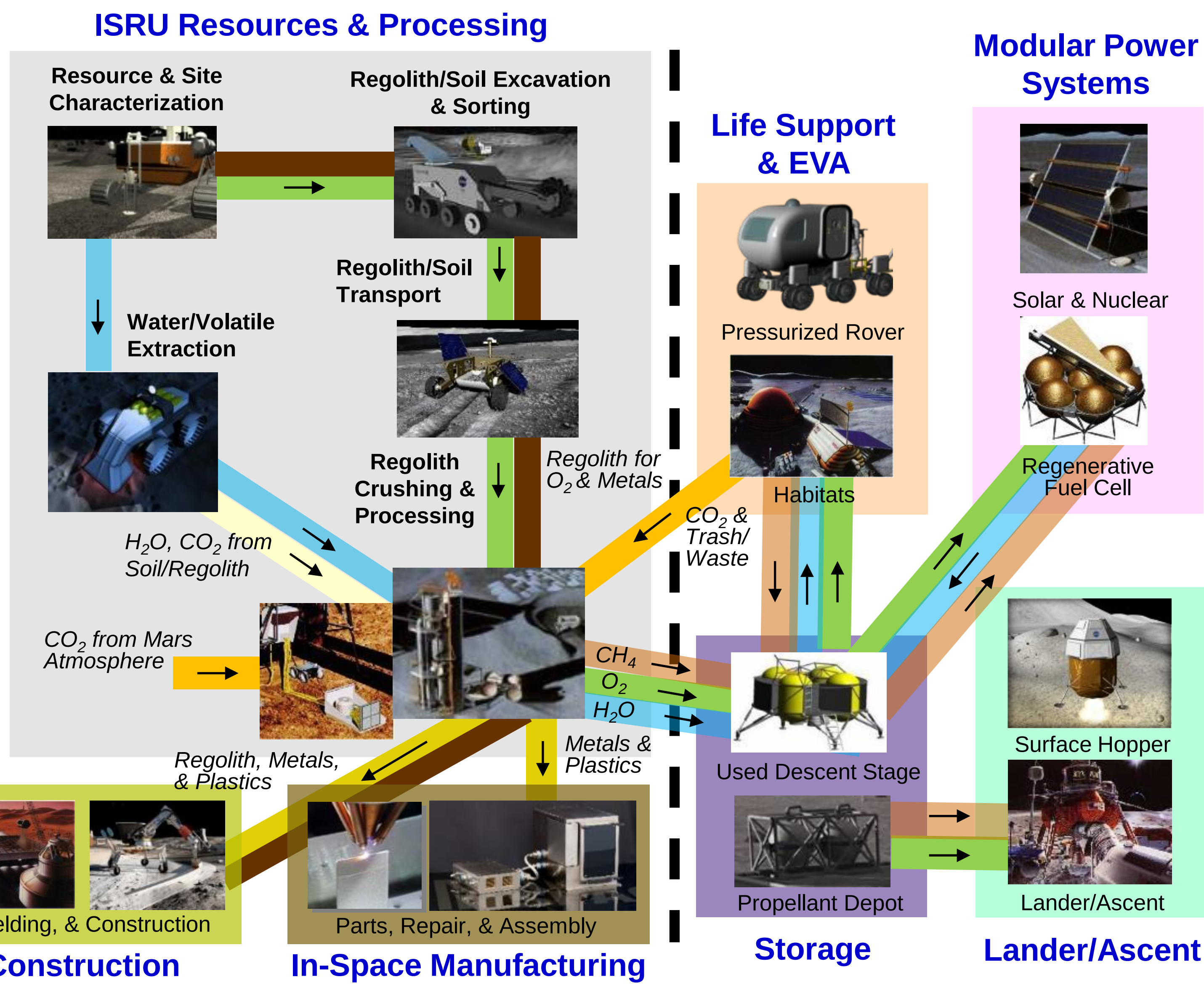
ISRU Integrated with Exploration Elements
(Mission Consumables)

ISRU Functions & Elements

- Resource Prospecting/ Mapping
- Excavation
- Regolith Transport
- Regolith Processing for:
  - Water/Volatiles
  - Oxygen
  - Metals
- Atmosphere Collection
- Carbon Dioxide/Water Processing
- Manufacturing
- Civil Engineering & Construction

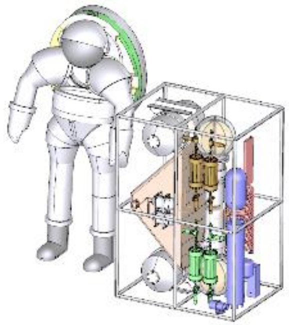
Support Functions & Elements

- Power Generation & Storage
- O_2, H_2, and CH_4 Storage and Transfer



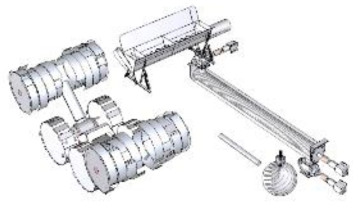
Mars Atmosphere & Water Resource Attributes

Atmosphere Processing



Atmosphere
- Pressure: 6 to 10 torr (~0.08 to 0.1 psi);
- >95% Carbon Dioxide
- Atm. temperature: +35 C to -125 C
- **Everywhere on Mars;** Lower altitude the better
- Chemical processing similar to life support and regenerative power

Granular Regolith Processing for Water

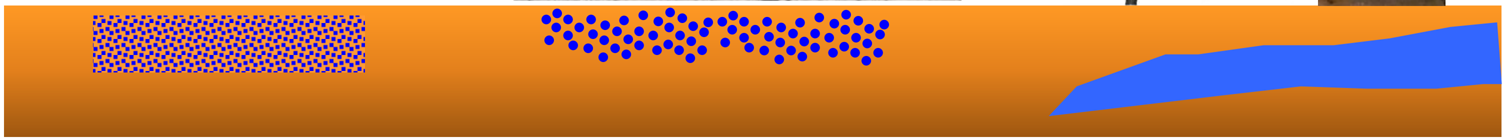


Mars Garden Variety Soil
- **Low water concentration 1-3%**
- **At surface**
- **Granular;** Easy to excavate
- **300 to 400 C heating for water removal**
- Excavate and transfer to centralized soil processing plant
- **Most places on Mars**; 0 to +50 Deg. latitude

Gypsum/Sulfate Processing for Water

Gypsum or Sulfates
- Hydrated minerals 5-10%
- **At Surface**
- **Harder material:** rock excavation and crushing may be required
- **150 to 250 C heating for water removal**
- **Localized concentration in equatorial and mid latitudes**

Icy Regolith Processing for Water



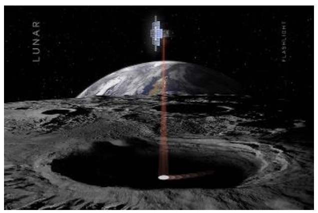
Subsurface Ice
- **90%+ concentration**
- **Subsurface glacier or crater**: 1 to 3 m from surface possible
- **Hard material**
- **100 to 150 C heating for water removal**
- Downhole or on-rover processing for water removal
- **Highly selective landing site for near surface ice or exposed crater;** >40 to +55 Deg. latitude

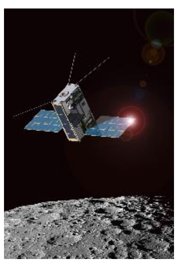
Increasing Complexity, Difficulty, and Site Specificity

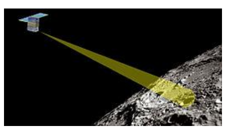
Current ISRU Missions Under Development

Resource Prospector – RESOLVE Payload

- Measure H_2O: Neutron spec, IR spec., GC/MS
- Measure volatiles – H_2, CO, CO_2, NH_3, CH_4, H_2S: GC/MS
- Possible mission in 2020

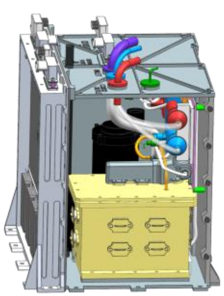






Orbiters/Cubesats

- Lunar Flashlight: Use laser and spectrometer to look into shadowed craters for volatiles
- Lunar Ice Cube: Broadband InfraRed Compact High Resolution Explorer Spectrometer (BIRCHES) instrument
- Skyfire Spectroscopy and thermography for surface characterization
- Mars 2022 Orbiter: Radar for ground ice and spectrometers for hydrated minerals



Mars 2020 ISRU Demo

- Make O^2 from Atm. CO_2: ~0.01 kg/hr O_2; 600 to 1000 W-hrs; 15 sols of operation
- Scroll Compressor and Solid Oxide Electrolysis technologies
- Payload on Mars 2020 rover